CCD Tests for the FAME Instrument Development Program

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Objective

Determine the limitations of the accuracy of FAME observations resulting from systematic effects of the optical and detector subsystems. In particular, what are the biases for individual (single) measurements of star positions and how will these be correlated with biases of other measurements of this same star and with measurements of other stars.

The primary issue is whether the image centroids can be determined to 1/700 pixel accuracy with an undersampled point spread function (PSF).

Background

The Full-sky Astrometric Mapping Explorer (FAME) is a small satellite designed to perform an all-sky, astrometric survey with unprecedented accuracy. FAME will create an accurate astrometric catalog of ~40,000,000 stars with visual band magnitudes 5 < V < 15 (there is a factor of 10,000 difference in flux from V=5 to V=15). For bright stars, 5 < V < 9, FAME will determine positions and parallaxes accurate to < 50 microarcseconds, with proper motion errors < 50 microarcseconds/year. For fainter stars, 9 < V < 15, FAME will determine positions and parallaxes accurate to < 300 microarcseconds, with proper motion errors < 300 microarcseconds/year.

FAME will also collect photometric data on these 40,000,000 stars in four Sloan Digital Sky Survey colors using filters over the four CCDs designated for photometry.

FAME will map our quadrant of the galaxy out to 2 kpc from the Sun providing the information needed to calibrate the standard candles that define the extragalactic distance scale, calibrate the absolute luminosities of stars of all spectral types for studies of stellar structure and evolution, and detect orbital motions caused by brown dwarfs and giant planets. FAME will not only improve on the accuracies of star parameters determined by Hipparcos but also expand by a factor of 8,000 the volume of space for which accurate astrometric parameters are known.

The FAME instrument is a telescope that will look at two fields of view (FoV) simultaneously. A mirror consisting of two flats tilted 65 degrees to each other directs light from the two fields of view into a single telescope (Figure 1). The spacecraft rotates with a period of 20 minutes, so the two fields of view scan along a great circle in the sky (Figure 2). Twenty-four CCDs are arranged in the focal plane of the FAME telescope (Figure 3). These CCDs are read out in scan mode (a.k.a. time delayed integration [TDI] mode - the charge is clocked as the star image moves across the device). The baseline plan is to use 2048x4096, thinned, backside illuminated devices with 15 micron pixels. The data are binned 5 x 1 on the devices, and two amplifiers are used on each device to read out the data at 0.382 ms/row, or 536,000 binned pixels/s per amplifier (Figure 4). The position of the stars is principally determined in one dimension at a time, namely the scan (spacecraft rotation) direction, which is nearly along the columns of the CCDs. The measurement of the star's position in the cross scan direction (along rows) is an order of magnitude less precise. The spacecraft also precesses with a period of 10 days, so there is also motion of the star images along CCD rows of up to five columns in one passage across a single CCD.

The two pupils of the FAME telescope are rectangular; the entrance apertures are 0.5m x 0.25m. The effective focal length is 7.5m, giving a plate scale of 0.0275 arcsec/micron or a pixel equaling 0.413 arcseconds on the sky. The telescope is diffraction limited, so at 600 nm the point spread function (PSF) of the optics is 1.2 pixels from minimum to minimum in the scan direction (Figure 5-7). The baseline FAME PSF is roughly given by:

$$PSF\,(p,q,l) = \left(\frac{1}{q}\sin\frac{pqC}{l}\right)\left[\frac{1}{p}\left(\sin\frac{ppS}{l} - \sin\frac{pp\,kS}{l}\right)\right]^2, \quad (1)$$

where λ is the wavelength, κ is the size of the central obstruction (equals 0.4 in the baseline design), *C* is the aperture size in the cross scan direction (25 cm), *S* is the aperture size in the scan direction (50 cm), *q* is the angle in the cross scan direction, and *p* is the angle in the scan direction. This equation approximates the FAME pupil as 2 rectangular apertures (Figure 8). See FAME/TC/SAO/012 for additional information on the FAME point spread function.

The maximum field angle is 1.23°. The exit pupil is 0.95 m from the detector, so rays at the maximum field angle impinge on the detector at 9.7° from perpendicular. Inside the silicon, the angle is about 2.7°.

A least squares fit or possibly a Baysian analysis will be used to determine the star's position from the FAME data. This is referred to as centroiding, or finding the centroid (or photocenter) of the star's image.

FAME will observe each star an average of 4000 times, scanning across the star at many different angles. To determine the ultimate precision of the star positions determined by FAME, we need to know the precision of the individual observations or individual centroid measurements.

More information on FAME can be found at http://aries.usno.navy.mil/ad/fame.

CCDs

It is clear from the literature that there is significant sub-pixel structure even with backside illuminated CCDs. In retrospect, this is not surprising due to the way in which 3 phase CCDs operate. Here the analogy of an array of light buckets we are all taught when we first hear about CCDs breaks down. CCD pixels are not square regions of collecting area; while CCD columns are separated by channel stops (potential barriers) built into the device, CCD rows are defined by the voltages set on the 3 phases of gates (Figure 9 and 10). Typically, two of the three phases are held at positive voltage and collect charge near them, and one phase is held negative to serve as a boundary between pixels.

Therefore, one would expect sub-pixel structure even with a backside illuminated device because the photons impacting the device near the gates held positive will collect photons better, and that the cartoons we show of CCDs being an array of square pixels is false because the pixel boundaries separating rows are loosely defined by the fields in the silicon.

In the current FAME design, the central peak of a point spread function moves 15 microns in 382 μs. During this time, the charge must be clocked from one pixel to the next pixel. Typically, six clock states (non-MPP mode) are used to transfer the charge from one pixel to the next (Figure 11). Exactly how best to clock the charge is an open question. Should the device be clocked as with a standard non-scanned observation, where all six states are of the same duration, or is it preferred to clock some of the states faster than others? Non-equal clock states would be required for operating the CCD in MPP mode, which requires seven clock states, one for integration and six for charge transfer. With all states of the same duration, the star image will move 1/6 of the distance across a pixel, then the voltages on the phases will change, moving the accumulated charge and altering the definition of a pixel. Since the subpixel structure is related to the phase structure, this might emphasize subpixel structure rather than average over it. Holding the phases at one state for most of the 382 μs integration, then quickly clocking the charge to the next pixel would better average the subpixel structure, but are there CTE and other problems associated with this? Do we want to average over subpixel structure, or will our knowledge of the subpixel structure be accurate enough for it to improve the precision?

The CCD camera for FASTT (8” transit circle telescope) at USNOFS operates with a CCD using non-equal state sizes (it is not operated in MPP mode) and achieves centroiding to 1/100 of a pixel.

Bright stars

FAME is required to observe stars with fluxes that differ by a factor of 10,000. This is beyond the dynamic range of CCDs available for FAME. The baseline design is to cover three of the twenty astrometric CCDs with neutral density filters to obtain the additional dynamic range. However, an additional objective of the CCD test program is to investigate alternate methods for observing bright stars.

On such possible method is the “gated clocking” technique. FAME will have a catalog of stars on board and the on board processor will be able to predict when a bright star is crossing a CCD. The clocking of this CCD could be temporarily stopped, allowing the star image to drift down several rows before the clock is restarted. This would separate the charge from the stellar image into one or more “integration points,” thus preventing the pixels from saturating or reaching a level where the response is non-linear (Figure 12 and 13).

Test would need to be performed to determine whether only the symmetrical integration points could be used in the data analysis, i.e. only pixel groups where the CCD clocking was stopped before and after the integration point. Tests will also need to be performed to determine the accuracy degradation resulting from the partially drift-blurred images.

Note that for the “gated clocking” technique, the master clock continues to run at the same frequency, only the voltages on the phases are not changing for one CCD. Thus, it is not expected that clocking cross talk that can occur for CCDs running at different frequencies will be a problem for this technique. However, care will have to be taken in the design and isolation of the power supply such that if a device is not clocking, the other devices do not see an increase in voltages that would effect their responses.

Other issues

Filtering astrometric CCDs:

John Geary and Dave Monet have strongly recommended using glass filters in front of the astrometric CCDs. They argue that glass is much more stable and consistent than the silicon in setting the wavelength range of the instrument. We will most likely place colored glass filters in front of the twenty astrometric CCDs. An open question is the wavelength of these filters – Monet argues that FAME should only operate in the red. The reason for this is that the PSF is narrower in the blue, hence the undersampling problem is even worse, and that the chromatic blurring of the PSF cannot be modeled to the accuracy required for most of the observed stars.

Split serial register operation:

Each FAME CCD shall operate with split serial readout registers feeding two amplifiers operating simultaneously. This is to reduce the analog to digital converters (ADCs) data rate from 1,072,251 binned pixels/sec to 536,126 binned pixels/sec. For the 12-bit resolution of the ADCs, the inherent linearity mismatches between one amplifier and the other on a CCD will probably not allow the accurate determination of centroids in the cross scan direction for stellar images straddling the serial-register split. This will effectively create a "dead zone" down the centerline of each CCD. Avoidance of such a dead zone has been the prime motivator at USNOFS for not operating CCDs for astrometry with more than a single readout amplifier in use at a time. This “dead zone” down the middle of the devices is something FAME can live with. However, if space qualified electronics – in particular, ADCs - can be identified that run above 1 MHz and also operate at low power, we would perform a cost-benefit analysis to select between single amplifier and split serial register operation of the CCDs, but the primary driver would be cost and simplification of the processing electronics.

Antiblooming:

Antiblooming is not a necessity for the prime requirements of astrometry, but may be extremely useful to prevent contamination along CCD columns from sources of excessive brightness. The 3-phase CCD technologies discussed in the FAME proposal might realize antiblooming either through clocked-antiblooming operation of a CCD built with entirely conventional structures, or via custom CCD construction incorporating antiblooming drains.

Regarding clocked antiblooming: this has been demonstrated as effective at USNOFS in the CCD camera for FASTT (8" transit circle telescope), in which the six clock-phase transitions that move the charge along the columns occur lumped together in time, rather than equally distributed in time as per the stated goals of FAME. The CCD involved is a Loral 2Kx2K with 15-micron pixels, so in some regards this technology mimics FAME. Recently, Gerry Luppino of the IfA gave a talk at the KBO conference in Flagstaff on the present qualities of large CCD array cameras, with specific attention to 2Kx4K CCDs produced at MIT/Lincoln Labs. Fred Harris put the question of clocked antiblooming to Gerry at the close of the talk, and he had an interesting reply (paraphrased): the quality of manufacture of LL CCDs has been found so high, and therefore the density of surface-state traps (required for clocked antiblooming) so low, that clocked antiblooming was deemed ineffective for the LL 2Kx4K CCDs. When Harris asked Gerry what might be the alternative, he responded that the incorporation of an antiblooming drain structure, coincident with the channel stops, was the likely route of technical evolution of the LL CCDs.

Antiblooming-drain structures are probably highly desirable for the FAME CCDs, but requires that such structures be engineered into the CCDs at design time. To the best of my knowledge, no presently available off-the-shelf 2Kx4K CCDs incorporate an antiblooming drain, hence for FAME to realize antiblooming, a new CCD foundry effort must be made.

The MIT/LL CCD devices can antibloom to a factor of 100,000 using drains down the center of the channel stops.

Transfer-gate:

It is assumed in this memo that the FAME CCDs are equipped with a transfer gate separating the image area of the device from the serial register, preventing charge from moving back to the image area from the serial register as it is being clocked out. Without a transfer gate, the entire serial register would need to be read out while the clock phase adjacent to the serial register is biased off. Tunneling through this clock phase could not be avoided.

The MIT/LL devices do not have transfer gates.

Transfer-gate tunneling:

Several makes of CCDs with 2K serial registers exhibit a process known as transfer-gate tunneling. When this occurs, charge from a high-level pixel being transported along the serial register is able to tunnel (in the quantum mechanical sense) through the barrier of the transfer gate back into the image area adjacent to the transfer gate, and thus be deposited erroneously. The tunneling locations are typically fixed along the cross-scan axis.

The work-around for transfer-gate tunneling at USNOFS has been to insure, in the timing of the image-area pixel clocks, that the clock phase adjacent to the transfer gate is also biased off during the entire time that the serial readout is taking place. The combined barrier of both the transfer gate and the adjacent clock phase being off during serial transfer has been entirely effective at preventing the tunneling phenomenon. However, this fix is unavailable to FAME due to FAME's intention of distributing the pixel-clock transitions in the time domain, which implies that for 2/6 of each line time only the transfer gate will provide a barrier to tunneling.

If off-the-shelf CCDs are to be used in FAME, then transfer-gate tunneling must be investigated for those CCDs under FAME operating conditions early in the testing program. If FAME is to founder new CCDs, then the structure of the transfer gate should be explicitly addressed so as to minimize the possibility of such tunneling.

Serial pixel full well:

The full well levels for the FAME CCD are required to be:

Pixel Full Well	>100,000 e-
Serial Full Well	>100,000 e-
Summing-Well Full Well	>450,000 e-

Signal chain electronics:

The signal processing for the CCDs is a non-trivial issue. If we use, as suggested by Lockheed Martin in the FAME proposal, a 12 bit ADC system with three gain settings, such a system may have idiosyncracies not evident in a 16 bit test system. This system will also need to be tested, so ideally, the CCD tests described here will be performed not only using a flight-like device but also using a flight-like signal chain system.

QE dependence on position:

Recently delivered devices from SITe have variations in QE(λ) dependent on position on the device. The wavelength response changes by up to 30% from center to edge. The FAME devices will need to have uniform QE(λ).

MPP operation:

Should the FAME CCDs be operated in Multi-Phase Pinned (MPP) mode? The advantages are a much lower dark current, a reduction of the surface residual image defects, and a greater tolerance for ionizing radiation environments. The disadvantage would be a reduction in the full well of the pixels by as much as 50%. This is a serious disadvantage due to the dynamic range required of these devices for FAME and the restrictions of word size available from low power ADCs.

MPP mode would also require that the clocking of the device would have seven states, one state the MPP/integration state and six charge transfer states.

High resistivity CCDs:

If FAME cannot use off the shelf CCDs and must undertake a CCD development program (not possible with our current schedule), we should consider high resistivity CCDs (see http://pdg.lbl.gov/~deg/ccd.html). The advantages would be a better red response (between 800-1000 nm) on a thick device, therefore mechanically better for launch stresses and saving the time required for thinning. The disadvantage would be the requirement to test the devices to determine their behavior in a radiation environment.

Questions to answer

Drift-scan / clocking issues:

1) What is the best way to clock the CCD to achieve the best centroiding precision?

2) Does integrating along columns in drift-scan mode average out the device's subpixel structure?

3) Does the readout rate affect the precision (this also involves the choice of ADC)?

4) Does the centroid position in the cross scan direction effect the centroiding precision?

5) What is the effect of the star track crossing a channel stop (crossing a column boundary)?

6) Should clocked antiblooming be used?

7) Is transfer gate tunneling an issue?

PSF issues:

8) What is the precision as a function of PSF size?

9) What is the precision as a function of PSF shape (rectangular vs. round)?

10) What is the precision as a function of PSF structure or complexity; how do the FAME central obstructions and mirror openings effect the precision?

Device Manufacturing Issues

11) Which device design provides the optimal performance?

12) What is the effect of masks used in CCD manufacturing (periodicities in the CCD structure?

13) What is the effect of the variations in CCD thickness within a device?

14) How consistent are these effects in devices from the same lot?

15) Should the FAME devices be operated in MPP mode?

16) Should the FAME devices have antiblooming drain structures?

Stellar Source / Wavelength Dependent Issues:

17) How does the PSF and subpixel structure vary with color?

18) How does the accuracy vary as a function of star type?

19) Are colored glass filters required on the astrometric CCDs and if so what wavelength passband is optimal?

Processing Issues:

20) What is the optimal technique for processing these CCD images?

21) Can the knowledge acquired from subpixel QE mapping be used to improve precision?

Other:

22) How will the space environment - principally radiation and condensation - effect the centroiding accuracy?

Tests To Perform

1) Perform standard CCD characterization tests - system gain, CTE, QE (as a function of wavelength), linearity.

2) Static pencil beam test of charge collected in the pixel on which the beam falls and 8 or 24 neighboring pixels (Jorden et al.). The spot size of the beam should be much smaller than the pixel. Test varying the:

- A) The state of the 3 phase CCD used for integration
- B) Spot position in the scan and cross scan direction
- C) A range of wavelengths between 400 and 900 nm
- D) A range of intensities, especially outside the linearity range of the CCD and near full well
- E) For a range of incident angles (from 90° to 82°)

3) Repeat tests described in 2) but with the CCD operating in scan/TDI mode with the beam moving synchronously with the CCD clocking along the CCD columns. These test will be best performed with more than one spot with varying separations. Also test with the beam moving at a small angle to the CCD columns such as will be the case with stars moving across the FAME detectors. Another technique would involve a narrow slit slightly angled relative to the pixels moved synchronously with the CCD clocking. Perform these tests clocking the CCD with equal and non-equal duration.

4) Test using MPP mode if device is MPP capable.

5) Test with clocked antiblooming.

6) Test device for transfer gate tunneling.

7) Test for inter-amplifier cross-talk from operation with a split serial register.

8) Perform the tests described in 3) but with many spots (with circular, Gaussian PSFs. Vary the PSF width from 1.2 pixels to 5 pixels.

9) Repeat the test described in 6) but with a model of the actual FAME PSF.

10) Determine the pixel positioning uniformity using tests like the one described in Shaklan et al.

11) Test device response as a function of applied voltages.

12) Determine whether the voltages on the CCD are a function of the field of view being observed.

13) Test gated clocking method for bright stars.

Conclusion

There is little point to performing tests on a CCD other than one that has an architecture identical to one that is a candidate for flight. Our current schedule (launch 2003) does not allow time for a CCD development program, so we must concentrate our efforts on devices that are available in quantity (~50) within the year. Our primary concern is obtaining a candidate device for use in testing to help use resolve many of the above questions so we can develop requirements for the FAME CCDs.

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"High-precision measurement of pixel positions in a charge-coupled device"

Appendix A: CCD Suppliers

	In house thinning	Transfer gate	MPP	Antiblooming	Split serial register	Web site
Lockheed Martin Fairchild	under development	?	?	?	?	none
Lincoln Labs/MIT	yes	no	?	yes	yes	
SITe	yes	?	yes		yes	www.site-inc.com
EEV	yes	?	?	?	?	www.ccd.eev.com

	Pixel size	Full well	Comments
Lockheed Martin Fairchild	15µm	?	Can they get up to speed for thinning a quantity of devices?
Lincoln Labs/MIT	15µm (9µm available)	no	

SITe	15μm	70,000 measured	Unreliable delivery, devices not to spec, wavelength response changes by 30% from corner to edge
EEV	13.5μm	?	

Appendix B: Attendees at Lincoln Laboratories meeting of 12 Nov 98

Name	Institution	Telephone	E-mail
Bernard Kosicki	MIT/LL	781-981-7874	kosicki@ll.mit.edu
Jim Phillips	SAO	617-495-7360	jphillips@cfa.harvard.edu
Robert Reasenberg	SAO	617-495-7108	reasenberg@cfa.harvard.edu
Marvin Germain	USNO	520-773-4868	meg@sextans.lowell.edu
John Geary	SAO	617-495-7431	geary@cfa.harvard.edu
Dave Monet	USNO	520-779-5132	dgm@nofs.navy.mil
Barry Burke	MIT/LL	781-981-0680	bburke@ll.mit.edu
Tom Lind	MIT/LL	781-981-4448	lind@ll.mit.edu
Ken Seidelmann	USNO	202-762-1441	pks@spica.usno.navy.mil
Scott Horner	USNO	202-762-0381	shorner@usno.navy.mil
Robert Reich	MIT/LL	781-981-7875	reich@ll.mit.edu

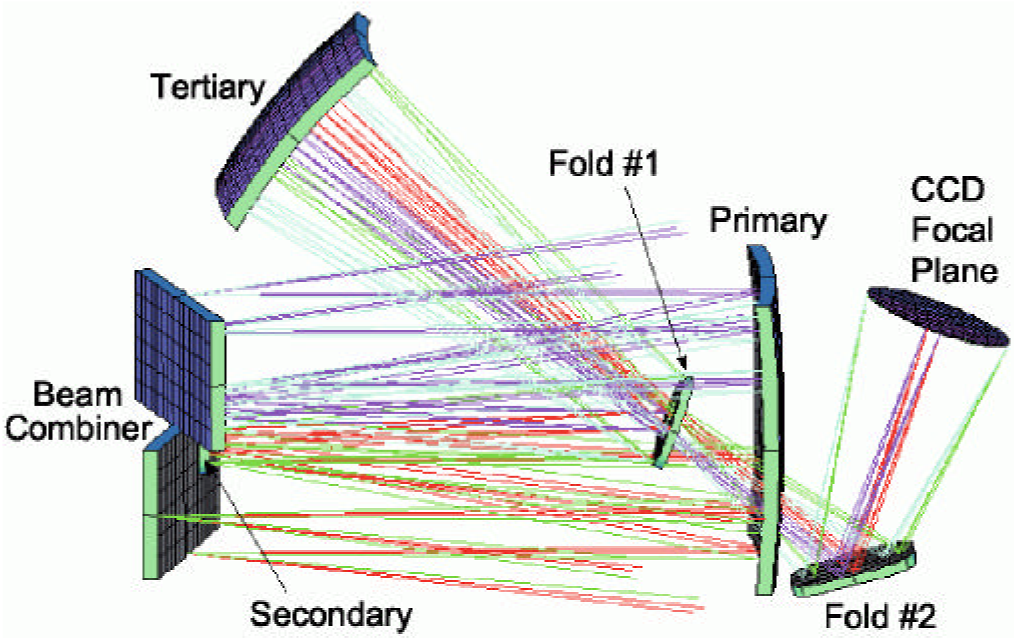

Figure 1: FAME optical ray trace diagram

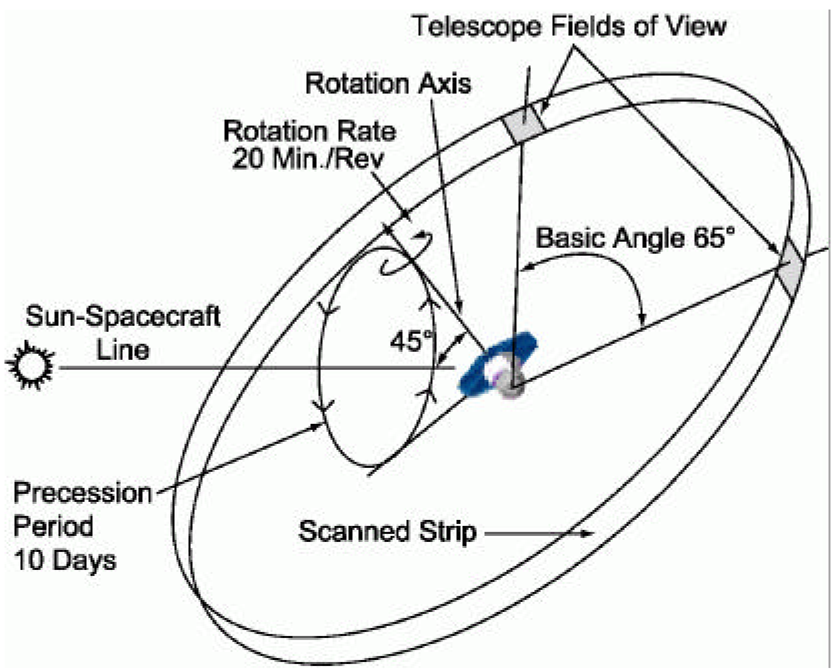

Figure 2: The two fields of view of FAME scan across roughly the same great circle on the sky as the spacecraft rotates. The two fields are separated by 65°.

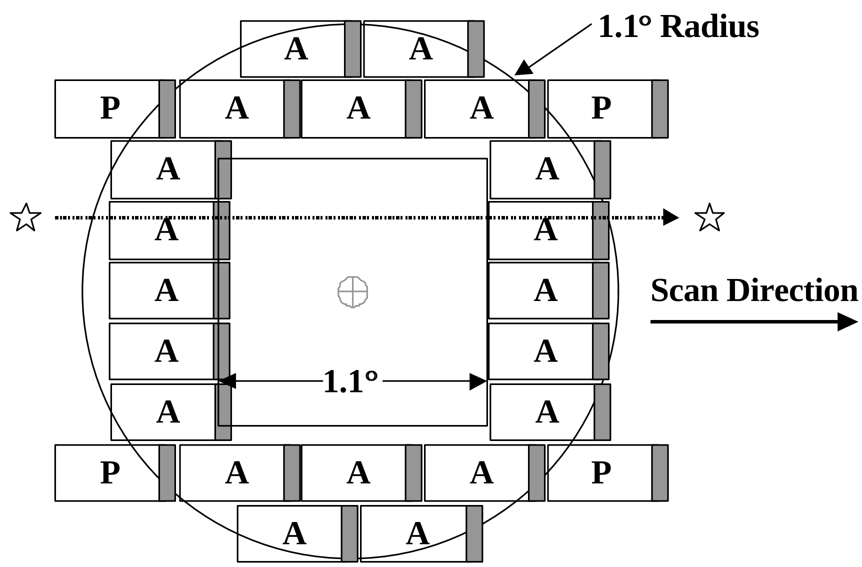

Figure 3: The FAME focal plane. The CCDs marked with "A" are the astrometric CCDs; those marked with "P" are the photometric CCDs. The gray indicates the amplifier (non-buttable) side of the device where the split serial register and two amplifiers are located. As the spacecraft rotates, the star images move from left to right in this view.

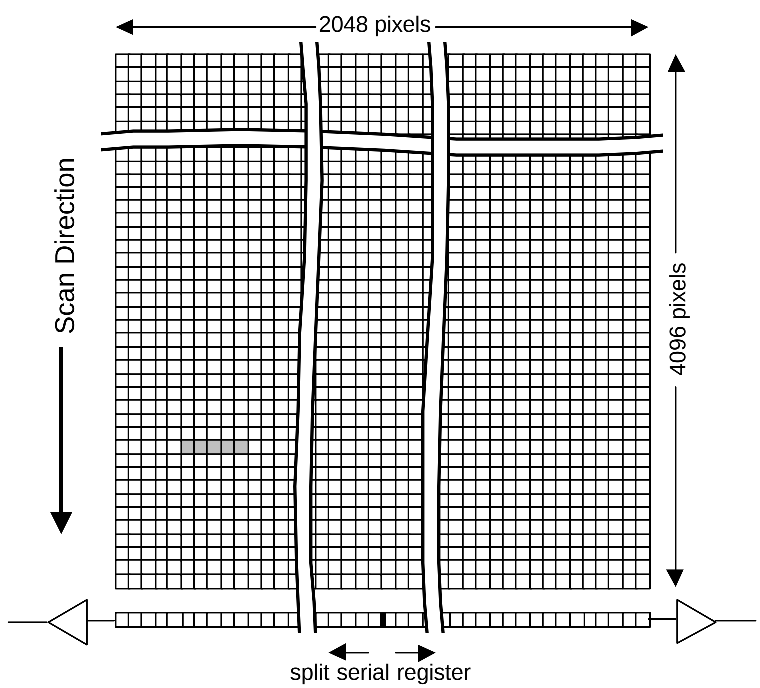

Figure 4: View of the backside illuminated 2048x4096 CCDs. The baseline pixel size is 15µm. FAME CCDs must have two good amplifiers on the same serial register. The pixels are binned in the cross scan direction by 5 (in the summing well) as is shown by the gray pixels.

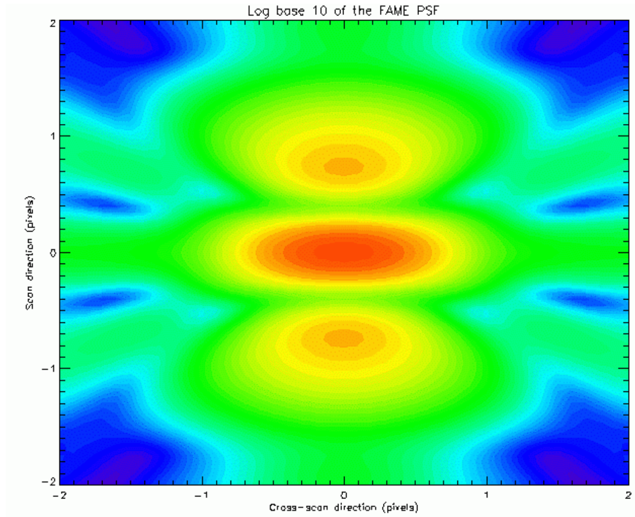

Figure 5: A contour plot of the $\log_{10}$ of the FAME PSF

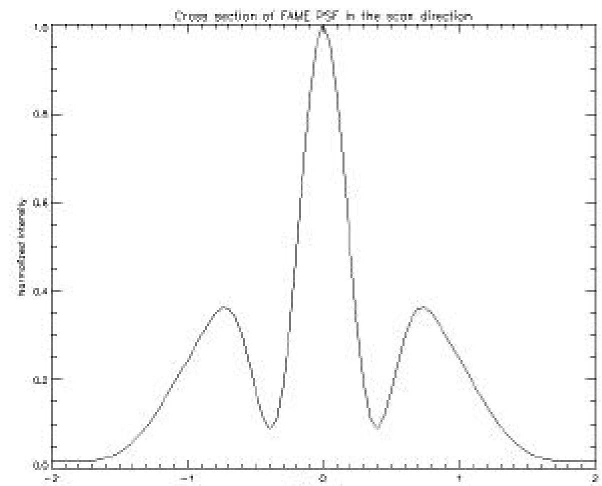

Figure 6: Cross section of the FAME PSF in the scan direction

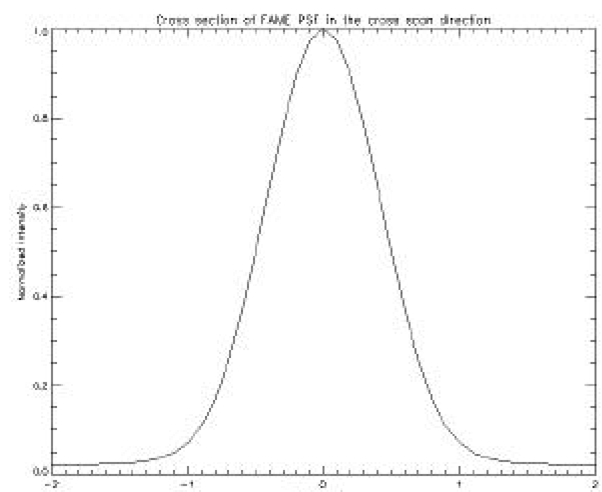

Figure 7: Cross section of the FAME PSF in the cross scan direction

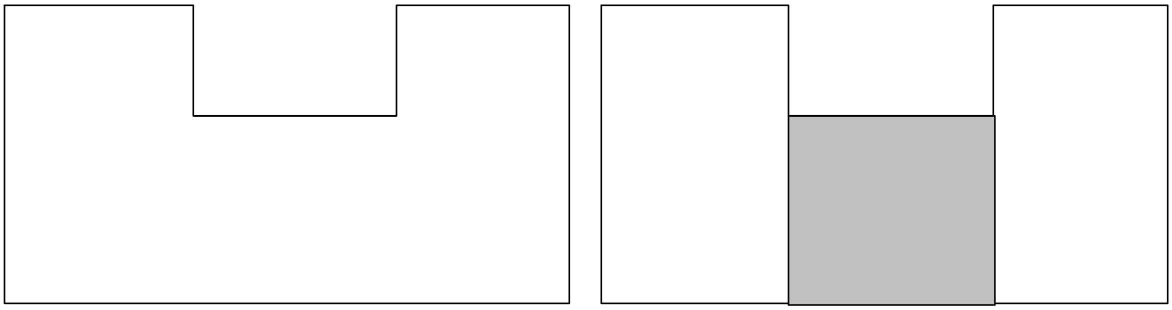

Figure 8: The left side shows the pupil of the FAME telescope. The right side shows the pupil as approximated by Equation 1, as two rectangular apertures.

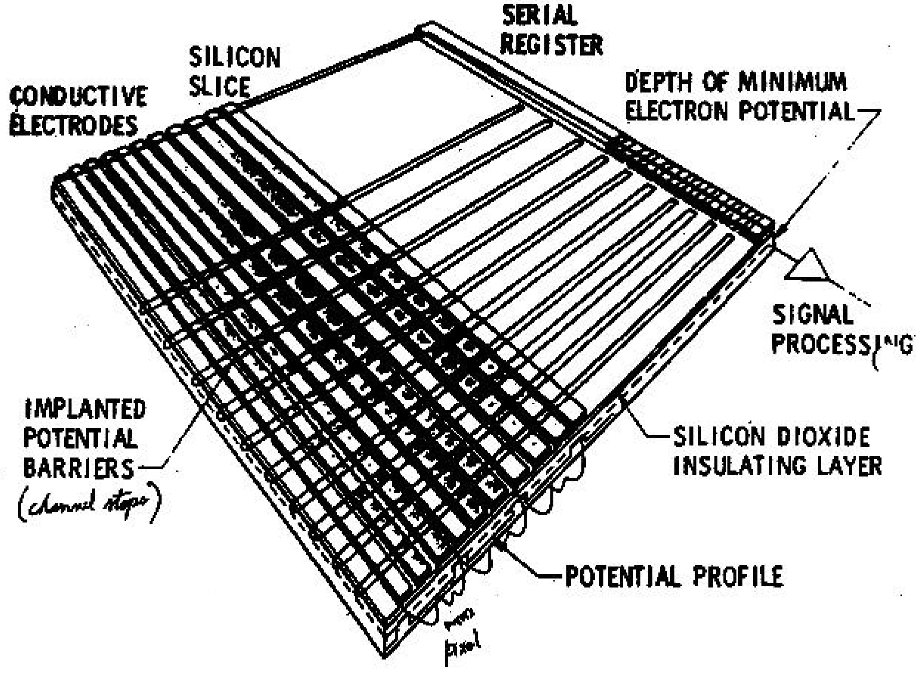

Figure 9: Basic structure of a CCD. Note the implanted potential barriers (channel stops) between columns. For a 3 phase CCD, 3 conductive electrodes comprise 1 pixel.

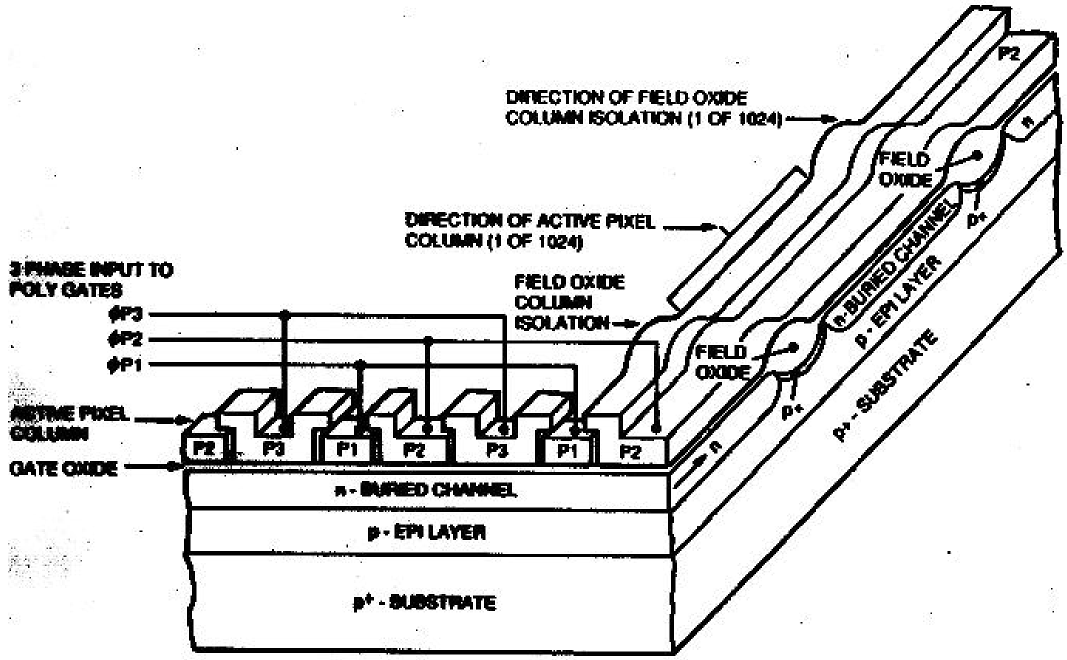

Figure 10: Basic architecture of a 3 phase CCD. Note that pixels are not distinctly separated from row to row. As FAME scans, the star image will smoothly move from gate to gate along the column, while the charge will move in discrete states.

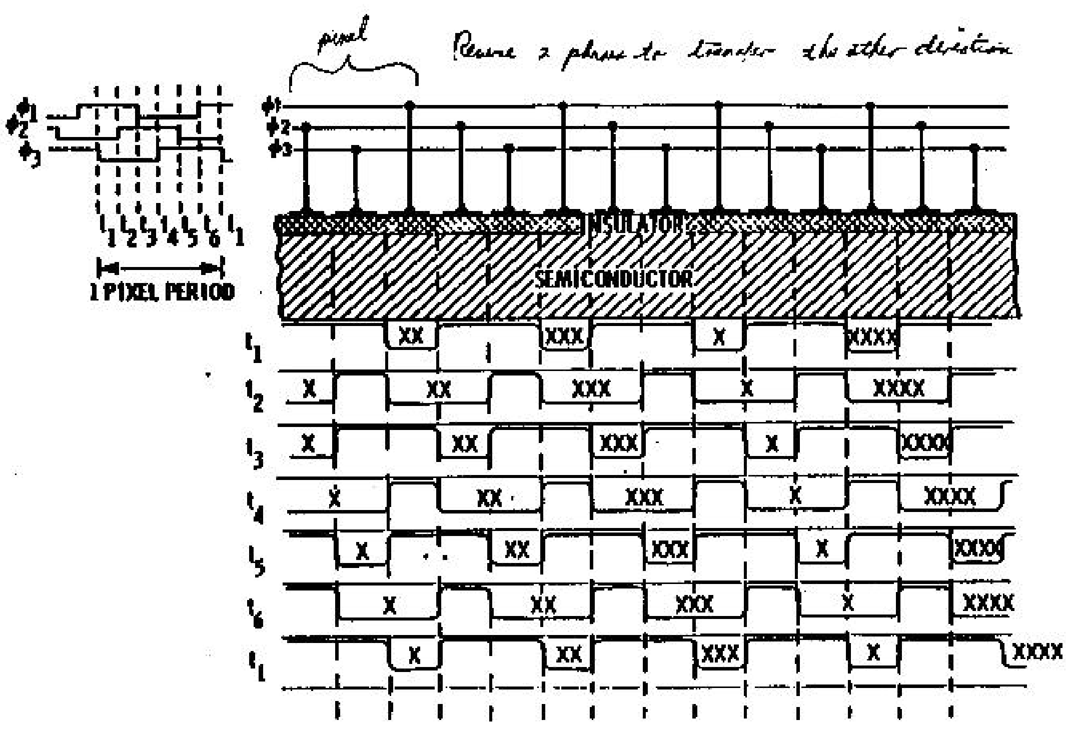

Figure 11: Clocking diagram for a 3 phase CCD run using 6 evenly spaced clock pulses per row. A CCD running in MPP mode will have 7 clock pulses per row with the 7th pulse being the MPP/integration phase.

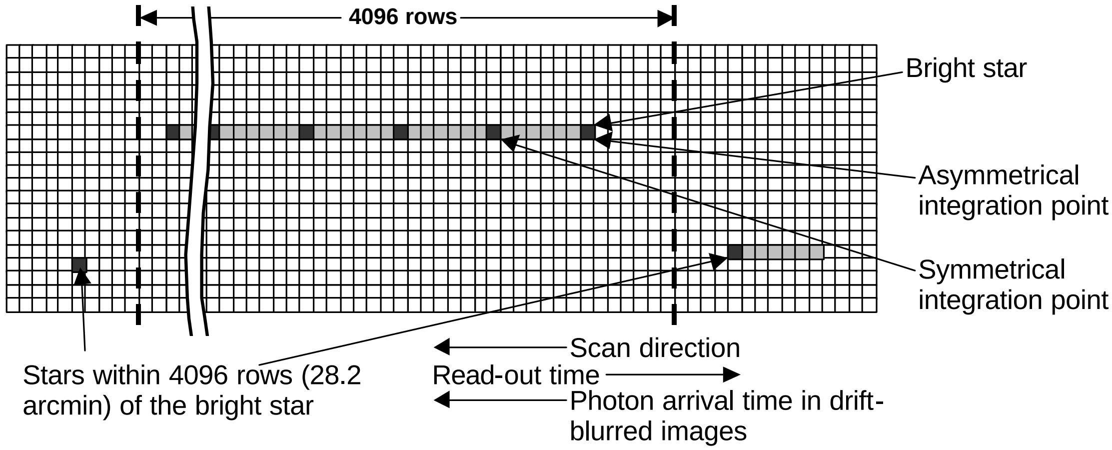

Figure 12: Gated clocking for bright stars, option 1. Here the CCD clocking would be suspended when a bright star is on the device, allowing the star to drift across the device without the accumulated charge moving synchronously with it. Clocking would be restarted at intervals. Dark squares show locations where the CCD clocking and thus the star is moving synchronously with the charge on the CCD; we will refer to these as "integration points." Gray squares show where the star image is moving relative to the CCD charge and is thus the image is blurred. It is presumed that only the integration points have blurred images (gray) on both sides, hence are symmetric, will be centroided and used for the astrometric solution.

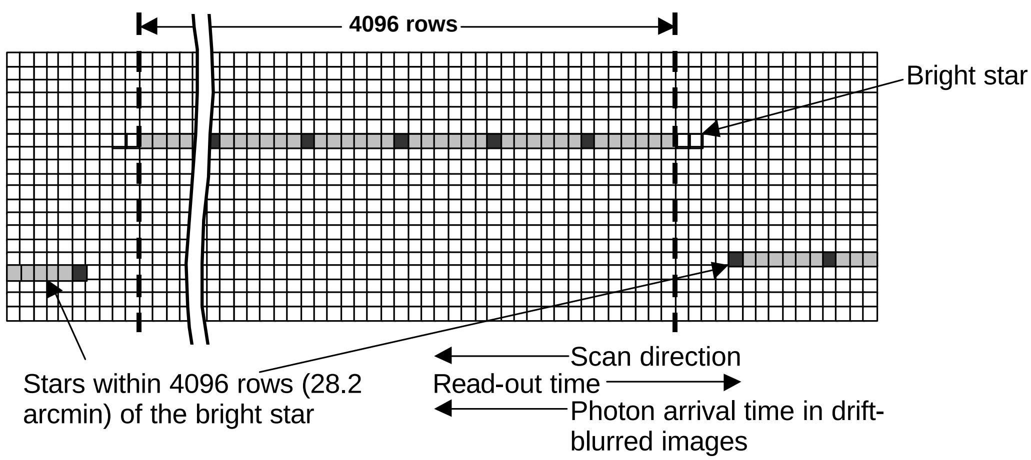

Figure 13: Gated clocking for bright stars, option 2. Similar to Figure 12, but here the CCD clocking is stopped before the bright star appears on the device. Thus there are no asymmetrical integration points, but the range of time in which the CCDs may not be clocking is longer, hence effecting the images of a larger area of the sky around the bright star.